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A flood decrease strategy based on flow network coupled with a hydraulic simulation software [1]

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Abstract: Flood is a natural phenomenon, usually sudden and a calamitous event with devastating consequences and serious effects on the society, the environment and the economy. Thus, more and more research efforts have been carried out and many solutions have been implemented in the aim to control their impact. In order to divert or block the excess water due to flooding, hydraulic structures such as retaining walls, retention ponds, dams, etc. are necessary and require the use of operation strategies to manage the complex water system. In this paper, a flood decrease strategy based on the graph theory is proposed in order to manage the control of the water storage and release from reservoirs along the river. This river-Tanks system is modeled by a dynamic network and the management problem is formulated as a minimum cost dynamic flow problem with some additional constraints. Then, this main problem is reduced into a set of low dimensional dynamic sub-problems, for which the dynamic network is extended into a static network solved using a heuristic method. Thereby this single commodity flow problem with additional constraints is modeled as a mixed integer linear program. Finally, the program is combined with a specialized hydraulic simulator to simulate the water transfer and the exchange between the reservoirs and the river. The proposed approach was applied on the Bastillac area and results obtained for a 100-year flood case are given, illustrating that the strategy ensures a weak downstream flow peak and a reduced impact.

Keywords: Dynamic networks, flood control strategy, water transfer simulation.

1. INTRODUCTION

A flood is an overflow water that submerges land which is generally dry. It usually happens as an overflow of water from the low-flow channel of a river. In order to divert or block the excess of water due to flooding, and in particular to avoid downstream flooding of the river, hydraulic structures are necessary (such as retention ponds, dams, etc). Those structures need operation strategies that help managing a complex water system. Attenuating flood consists in putting water in the right place at the right time. The work presented in this paper describes a flood retention areas management method for the attenuation of the river overflow. In this aim, a network flow model of the river equipped with tanks (river-tanks system) and an optimization algorithm are proposed. Indeed, in the last few years, optimization has constantly proven its effectiveness in solving real problems. Thus, many studies have been done to manage reservoirs releases under different concepts, such as scheduling, stochastic dynamic programming, meta-heuristics, etc.
Qi et al. (2015) have developed new scheduling approaches using artificial intelligence for a multi-objective optimization for reservoir flood control management. Li and Ouyang (2015) proposed a generalized multi-objective flood control model. Archibald et al. (2006) proposed an operation policy for a multi-reservoir control problem, using stochastic dynamic programming, based on the decomposition of the problem into a number of independent sub-problems, where each one is formulated as a low dimensional stochastic dynamic program. Kelman et al. (1990) explored the use of sampling stochastic dynamic programming in order to generate efficient and fast operating policies. Another application of stochastic dynamic programming was given in Liu et al. (1990), based on a two stages decision process. Ahmed and Sarma (2005) used genetic algorithm (GA) in the aim to find an optimal operating policy for a multi-reservoirs system; while Moravej and Hosseini-Moghari (2016) proposed an application of the Interior Search Algorithm (ISA) to solve multi-reservoirs system operation optimization problems. They showed in their work the efficiency of this method comparing to other methods like non-linear and linear programming, genetic algorithm and other meta-heuristics.
In Nouasse et al. (2013) the River-Tanks system with one gate is presented as a dynamic network wherein a mini-

[1] This work was partially supported by the urban community of Le Grand Tarbes.

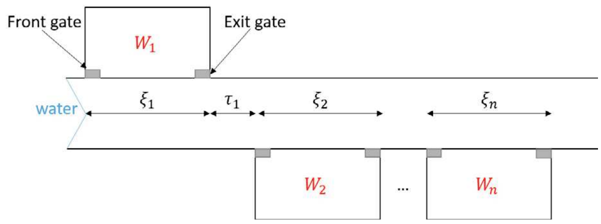

Fig. 1. River-tanks system

mum cost flow problem is solved using a greedy algorithm which consists of solving at each iteration a static flow problem where the capacities of the edges depend on the previous results obtained so far and on the measured flow rates in front of each tank. However, in the case where the tanks are not big enough to store all the overflowing water, at the time when the tanks are full the flood is undergone, the method can no longer manage the overflowing. In this case, this method could be improved if the decision made at each iteration took into account the flow rates that may come in the next iterations, in other words if the flow evolution is prognosticated. Optimization methods have been proved to be very efficient when they are used with simulation modelling. A comprehensive survey and bibliography is given by Rani and Moreira (2010). Nowadays many hydraulic modelling softwares exist, such as SIC (Baume et al. (2005)), HEC-RAS (Brunner (1997)), TELEMAC (Galland et al. (1991)), MIKE 11 (DHI (2009)), etc. The majority of those softwares, solve the Saint-Venant equations (de Saint-Venant (1871)). In this paper an operational management strategy of tanks equipped with 2 gates (entrance and exit) based on graph theory is proposed. In order to reduce flooding in the downstream of the river, the tanks connected to the waterway are managed to hold extra water during the flood. This management problem is formulated as a minimum cost flow problem in a dynamic network over a time horizon H. This implies the knowledge of the incoming flow to the upstream of the river during all the horizon H. However, the dynamical aspect complicates its resolution and therefore increases its execution time. Furthermore, in actual cases the incoming flow is known only when it reaches. Thus, the main problem is reduced into a set of low time dimensional dynamic sub-problems considering a k length time window wherein the incoming flow rates can be estimated. The estimation can, for example, be done by computing a trend from previous measured values or by using precipitation forecasts combined with rainfall-runoff models (Fourmigué and Arnaud (2010), Scharffenberg (2013)). In order to solve each sub-problem, the dynamic network is extended into a static network, which can be solved using a heuristic method described thereafter. Thereby this single commodity flow problem with additional constraints is modeled as a mixed integer linear program. Finally, the program is combined with a specialized hydraulic simulator named SIC to emulate the flow rates at each station of the river.

In the following, the methodology is firstly described, a case study is presented and the results obtained by applying the strategy on this case are given.

2. METHODOLOGY

The objective of our study is to find the optimal quantity of water over time that should cross each gate of each tank during the entire time horizon H, in order to minimize the global flood arriving to the downstream of the river wherein the area to protect. The time delays between the tanks and the gates are denoted respectively by τ and ξ as shown in figure 1. Each tank has a maximum storage capacity U_i that cannot be exceed, and a storage cost C_i.

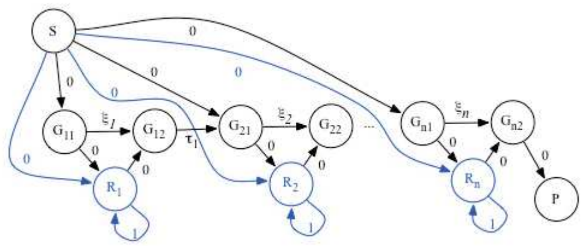

Fig. 2. Dynamic graph associated with the system

2.1 Dynamic network

In this section, the sub problem wherein the future flow rates over a time window are known, and for which a minimum cost flow problem should be solved is considered. The corresponding dynamic network, G, over this sub-horizon, represented in figure 2, is defined by $G = (V, A, \tau', C', U)$, where:

$V = W \cup S \cup P$, with S : the source, P : the arrival point and $W = G_1 \cup G_2 \cup R$ nodes representing the tanks. With G_1 : entering gates, G_2 : exciting gates and R : the reservoirs.

A : the set of arcs representing the flow in the river and the reservoirs.

$\tau' = \tau \cup \xi$: the set of time delays as shown in the figure 1. It is assumed that the flow crosses instantly the gates, which means the transit times of the arcs linking the reservoirs with their gates are null.

$C' = C_s \cup C_x$: where C_s is the set of storage costs and C_x is the set of overflow's costs.

U : the set of arcs capacities.

It has been proven that the minimum cost dynamic flow problem is weakly NP-hard problem (Skutella (2009)), which complicates its resolution phase. Nevertheless, it can be reduced to a minimum cost static flow problem on a pseudo- polynomial time. For this purpose, the dynamic network is reduced into a static network, named extended network thereafter, as introduced by Fulkerson (1966). This extended network contains a copy of the vertex set of the dynamic network for each iteration. The transit times are implicitly expressed by the connection between the iterations, i.e. the transit times are represented by arcs linking those copies as shown in the figure 3.

The sub-problem corresponding to the time window $I_t = [t, t + k]$ with lenght k, where the incoming flow rates are estimated, needs, as an input, the values of the flow rate in front of the gates at t. This values are provided by SIC (Simulation of Irrigation Canals), an hydraulic numerical modeling software developed by IRSTEA Montpellier (Baume et al. (2005)). The SIC software permits the simulation of the hydraulic behavior of irrigation canals and rivers, in steady and unsteady flow conditions. SIC allows us to simulate the behavior of the river flow due to the operations made on the gates.

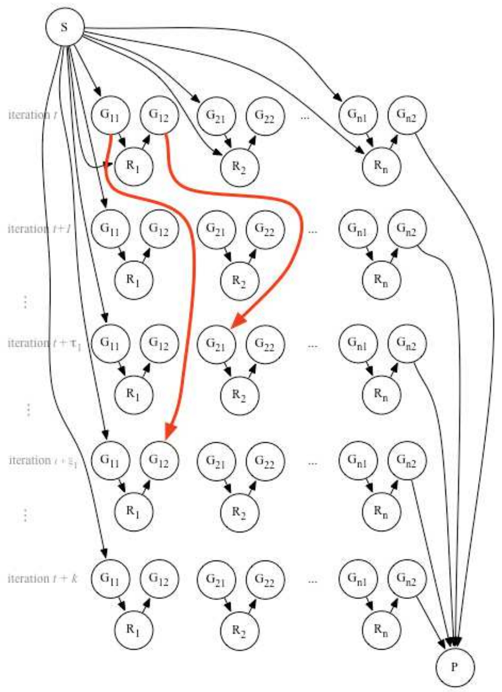

Fig. 3. Extended graph associated to the sub-problem

2.2 Mathematical formulation

In this section the problem is formulated as a minimum cost dynamic flow problem with some additional constraints, where the flows are represented by non-negative variables : $qin_i(t)$, $qout_i(t)$ stand for the river flow at the level of the front, exit reservoir gates respectively; $qr_i(t)$ and $qs_i(t)$ represent the flow entering and leaving the reservoir i; and $s_i(t)$ is the flow stored in the tank. $\mu_i(t)$ is a boolean variable equal to 1 if the tank i is releasing at time t. Then the problem can be formulated as the follow, where M is a large positive constant:

$$(P): min \overbrace{C_{x_{(G_n,P)}} \times Q_{max}}^{\alpha} + \overbrace{\sum_{l=t}^{t+k}\sum_{i=1}^{n} C_{s_i} \times s_i}^{\beta} \quad (1)$$

sc.

$$Q_{max} \geq (qout_n(l) - Q_{lam}) \; \forall l = t,...,t+k \quad (2)$$

$$qout_i(l) = qin_i(l-\xi_i) + qr_i(l) - qs_i(l-\xi_i) \; \forall i = 1,...,n \; \forall l - \xi_i > 0 \quad (3)$$

$$qin_i(l) - qout_{i-1}(l-\tau_{i-1}) = 0 \; \forall i = 2,...,n; \forall l - \tau_{i-1} > 0 \quad (4)$$

$$qin_1(l) = Q_{input}(l) \; \forall l = t,...,t+k; \quad (5)$$

$$s_i(l) = s_i(l-1) + qs_i(l) - qr_i(l) \; \forall i = 1,...,n \; \forall l = t,...,t+k \quad (6)$$

$$qout_i(l) \leq Q_{lam} + (1-\mu_i(l))M \; \forall i = 1,...,n \; \forall l = t,...,t+k \quad (7)$$

$$qr_i(l) \leq U_i \mu_i(l) \; \forall i = 1,...,n \; \forall l = t,...,t+k \quad (8)$$

$$M(1-\mu_i(l)) \geq qin_i(l) - Q_{do} \; \forall i = 1,...,n \; \forall l = t,...,t+k \quad (9)$$

$$qin_i(l), qout_i(l) \geq 0 \; \forall i = 1,...,n \; \forall l = t,...,t+k \quad (10)$$

$$0 \leq s_i(l) \leq U_i \; \forall i = 1,...,n \; \forall l = t,...,t+k \quad (11)$$

$$\mu_i(l) \in \{0,1\} \; \forall i = 1,...,n \; \forall l = t,...,t+k \quad (12)$$

The first term α of the objective function (1) represents the cost of damages, $C_{x_{(G_n,P)}}$, if Q_{max} reaches the downstream of the river, where Q_{max} is the highest flow over the entire time horizon which is calculated by the equation (2). The second term β represents the total storing cost. In this formulation, the conservation flow constraints are expressed by the equations (3), (4) and (6). The constraint (3) ensures that the river flow at the exit gate level of each tank i at any time t within $t - \xi_i > 0$, equals to what has

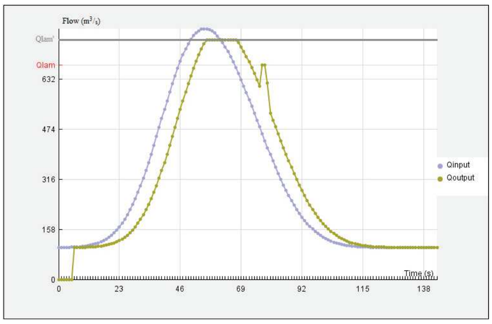

Fig. 4. Storage strategy

come from the river at the front gate level at time $t - \xi_i$ (time delay between the two gates of the tank i) minus what crossed the first gate at this exact same moment, plus the quantity that has been released from the tank i at time t (if $t-\xi_i < 0$, then the flow has not yet reached the exit gate that is $qout_i(t) = 0$). The constraint (4) makes the connection between the tanks, such that the river flow at the front gate level of each tank is equal to the flow sent from the previous tank at time $t - \tau_{i-1}$. For the first tank, this river flow is initialized by $Q_{input}(l)$, the flow measured at the upstream of the river (5). Finally the constraint (6) has for aim to update the storage. The constraint (7) ensures that the outflow from each tank would not exceed Q_{lam} in case the current tank is being released ($\mu_i(t) = 1$). Moreover, for safety reasons, a tank can be released only if the incoming flow rate is lower than $Q_{do} = 80\% Q_{lam}$. This condition is provided by the equations (8) and (9). The equations (10), (11) and (12) are related to the acceptable range for variables values.

2.3 Optimal threshold method

The objective of the proposed method is to compute the water quantity that should be stored or released from each tank during a river flood episode. Thus, the algorithm described is divided into two sections : storage and release. When the total storage capacity of the tanks is not enough to keep the entire flooding two strategies can be applied. Either the flow under Q_{lam} is stored until the total storage capacity is reached, or the peak of the food is reduced. In the first case, the flood is avoided for a short time and then undergone. In the second, the flood and the possible damages are reduced. In order the implement the second method it is necessary to compute the optimal threshold Q'_{lam} below which no water is stored in the tank even if the flow rate is higher than Q_{lam} as shown in figure 4. Thus, a new variable Q'_{lam} varying from Q_{lam} to Q_{peak} (the highest flow reached during the flood), is defined.

Let Q_{input} be the vector of the incoming flows to the upstream of the river in each iteration, with $dim(Q_{input}) = k$, and U_i the capacity of a tank. The value of a feasible solution obtained by a specific threshold is given by :

$$V(Store(Q_{input}, U_i, Q'_{lam}, s)) = \max_{1,...,k} Qout(t)$$

The value of the solution obtained for each $Q'_{lam} \in [Q_{lam}, Q_{peak}]$ returned by algorithm 1, are compared and the Q'_{lam} corresponding to the lowest one, is selected.

The outflow obtained by the algorithm 1, is then sent to the exit gate of the tank with a time lag, and the quantity

Algorithm 1 Store

Data: Q_{input} : incoming flows
U_i : capacity of the tank i
Q'_{lam} : storing threshold
s : vector of the stored flows
Results: Q_{out} : outflows
Variables : k : horizon's size
q : stored quantity at an iteration
s_d : available space in the tank
Initialization :
$k \longleftarrow dim(Q_{input})$
$s_d \longleftarrow U_i$
for $t = 1$ to k **do**
  if $Q_{input}(t) > Q'_{lam}$ and $s_d > 0$ **then**
    Stored quantity :
      $q \longleftarrow min\{s_d, Q_{input}(t) - Q'_{lam}\}$
    Calculate the outflow from the front gate :
      $Q_{out}(t) \longleftarrow Q_{input}(t) - q$
    Update the available space :
      $s_d \longleftarrow s_d - q$
    Update the stored flow :
    for $l = t + 1$ to k **do**
      $s(l) \longleftarrow s(l) + q$
    end for
  end if
end for

Algorithm 2 Release

Data: Q_{input} : incoming flows
s : vector of the stored flows
Q_{do} : restitution threshold
Q'_{lam} : storing threshold
Results: Q_{out} : outflows
T : total released flows
Variables : k : horizon's size
q_r : released flow
Initialization :
$k \longleftarrow dim(Q_{input})$
$T \longleftarrow 0$
for $t = 1$ to k **do**
  if $Q_{input}(t) < Q_{do}$ and $s(t) > 0$ **then**
    The released flow :
      $q_r \longleftarrow min\{s(t), Q_{lam} - Q_{input}(t)\}$
      $T \longleftarrow T + q_r$
    Update outflow :
      $Q_{out}(t) \longleftarrow Q_{input}(t) + q_r$
    Update the stored flow :
    for $l = t + 1$ to k **do**
      $s(l) \longleftarrow s(l) - q_r$
    end for
  end if
end for

that could be released from it is calculated using algorithm 2. This basic process consists in verifying that water can be released from the tank (i.e. the flow rate in front of the second gate is lower than Q_{do}, and the tank is not empty).

When water from the tank is released, it gives back a certain space available (additional tank capacity) that can be used for future storage. Therefore, several processes are launched increasing each time the capacity, as long as the value of the solution is improved (algorithm 3).

Algorithm 3 Optimal threshold method

Data: Q_{input} : incoming flows
Q_{lam} : overflowing threshold
Q_{do} : restitution threshold
U_i : capacity of the tank
Q_{peak} : highest flow reached during the flood
Results: Q_{out} : outflows
s : vector of the stored flows
Variables : I : boolean variable equals to true if an improvement can be done
T : total released flows
T_0 : previous total released flows
$Q1_{out}$: intermediate outflow
Initialization :
$I \longleftarrow true$
$T_0 \longleftarrow 0$
$s \longleftarrow 0$
while I **do**
  $Q1_{out} \longleftarrow \min_{Q'_{lam}=Q_{lam},\ldots,Q_{peak}} V(Store(Q_{input}, U_i, Q'_{lam}, s))$
  $(Q_{out}, T) \longleftarrow Release(Q1_{out}, s, Q_{do})$
  if $T > T_0$ **then**
    $T_0 \longleftarrow T$
    $U_i \longleftarrow U_i + T$
  else
    $I \longleftarrow false$
  end if
end while

3. OPTIMIZATION-SIMULATION MECHANISM

The optimal threshold method described previously, allows the resolution of the sub-problem under the $[t, t+k]$ time interval. The main problem over the time horizon H, is solved through the use of the real time strategy given in figure 5. The actual flow rates at t in front of the gates, qin, are emulated by SIC, since SIC provides flow rates in front of each gate using only data collected from one hydraulic measuring station established upstream. The data needed for the sub-problem, the incoming flows $Q_{input}(l)$, for $l \in [t+1, t+k]$ must be estimated, for example, by computing a trend from previous measured values or by using precipitation forecasts combined with rainfall-runoff models. Based on these data, the real time strategy consists in making at each moment t an operational decision based on the solution of the sub-dynamic problem corresponding to the interval $I_t = [t, t+k]$. The results of the sub-problem (ie the flow that should cross each gate during the interval I_t), are sent to the hydraulic simulator SIC in order to calculate the opening heights of the gates needed to obtain the exchange of the computed flow. SIC also gives back the river flow rates in front of each gate considering the operations made over the time window k. Thereafter, the algorithm solves a new sub-problem corresponding to I_{t+1} and launches a new SIC simulation with new instructions over the interval I_{t+1}. This process is given by the algorithm 4 and schematized in 5.

4. CASE STUDY

4.1 Site and hydrological description

The case study considered concerns the Bastillac area which is a parceling located in the town of Tarbes in the

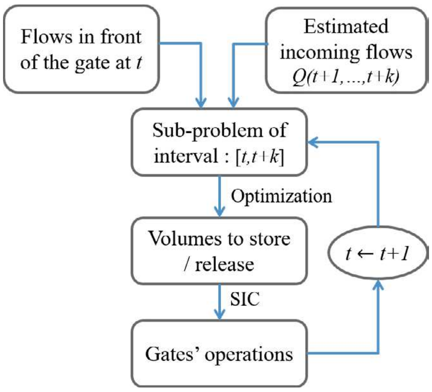

Fig. 5. Optimization-Simulation mechanism

Algorithm 4 Processus

Data: H : Horizon
n : number of tanks
Q_{lam} : overflowing threshold
Q_{do} : restitution threshold
U_i : capacity of the tank
k : size of the sub-problem
Results: q_{out} : outflows in the river at the level of each reservoir exit gate
s : vector of the stored flows
Variables : qin : flows measured in the river at the level of each front gate at t
Q : estimated flows in the river at the level of each reservoir front gate over $I_t = [t, t+k]$
Q_p : highest flow reached during the time window
Initialization :
$s_i(t) \longleftarrow 0 \; \forall i = 1, ..., n \; \forall t = 1, ..., H$
Initialize SIC
for $t = 1$ to H **do**
  $qin \leftarrow$ Read measures from SIC
  $Q \leftarrow$ Estimate flows over I_t
  $Q_p \leftarrow \max_{j=1,...,k} Q(t+j)$
  for $i = 1$ to n **do**
    $(q_{out_i}, s_i) \leftarrow$ Optimal threshold method$(Q(i), Q_{lam}, Q_{do}, U_i, Q_p)$
  end for
  set gates instructions in SIC
end for

south west of France. The Bastillac area is half surrounded by Echez river which borders it from the south and the east (figure 6). Thereby, this area is regularly flooded by the overflowing of the river. The flow rates of the Echez river are largely controlled and measured at the stations Louey ($90km^2$) and Borderes-sur-Echez ($168km^2$), and the station Maubourguet ($420km^2$) before the confluence with the Adour river. In addition, a flood warning station is located at the road bridge from Tarbes to Pau. The Bastillac area can be flooded when the flow rate of the Echez river is close to $60m^3/s$.

4.2 Planning

In order to protect the Bastillac area, different solutions were considered by the urban community of Le Grand Tarbes. Setting a flood expansion area is among these solutions. Here in, for this studied case, it is shown that

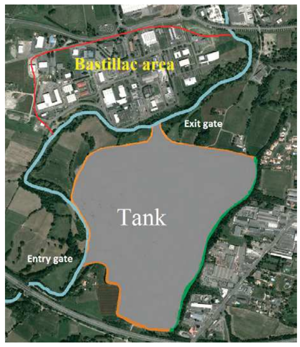

Fig. 6. Bastillac area reservoir system

controlling the flood expansion area, developing strategies for storage/restitution, and forecasting flow rates permits to reduce the volume of the retention pond, and thus the costs of construction. The front gate of the flood expansion area is planned to be established in the upstream of the Bastillac area, on the right side of the Echez river. Its purpose is to limit the inflow by storing a portion of the flood in the upstream area (figure 6). The fenced area covers a surface of 40 ha. For a dyke of 1 meter height, the volume of the reservoir is of $350.000m^3$. The flood expansion area will be equipped with check valves to its input and output.

Using a topographic survey, the river bed (lowest part the river valley) was modeled in SIC, and projected the reservoir to simulate the water transfer and the exchange between the river and the tank according to the commands of the algorithm. Since Borderes-sur-Echez station is closest to the Bastillac area, its data were used in this study. Various flow rates were extracted from Hydro bank in order to derive flood hydro-graphs which were used for applying the proposed method in the case of flood events with different characteristics (one or two peaks flood, various flow rate ranges and flood duration ranges, etc). Herein, the flooding of 25 January 2014 was chosen to illustrate the results obtained. The peak flow was $88m^3/s$ which corresponds to a return period of 20 years. A flood hydrology study of the Echez river over a chronicle decades led to a flow of $105m^3/s$ for a return period of one hundred years. In order to asses the ability of the future reservoir to reduce a 100-year flood, the flood hydrograph of 2014 floods was multiplied by a coefficient so that the peak flow become $105m^3/s$ instead of $88m^3/s$. The incoming flow rates are estimated over a 6 hours time window. In order to asses the results of our strategy, it was compared to an ordinary strategy consisting in storing when the flow rate exceeds Q_{lam} and release when it is below Q_{do}. For simplification, the ordinary manipulation is denoted $STR1$ and the one developed in this paper $STR2$.

4.3 Results

The results are presented in figure 7 in which the incoming flow in blue line corresponds to a 100-years flood, the overflowing threshold, Q_{lam}, in red discontinuous line is equal to $60m^3/s$, the restitution threshold, Q_{do}, in green discontinuous line is equal to $50m^3/s$ and the outflow obtained at the downstream of the river is given in yellow when the ordinary strategy $STR1$ and in purple for the proposed strategy $STR2$.

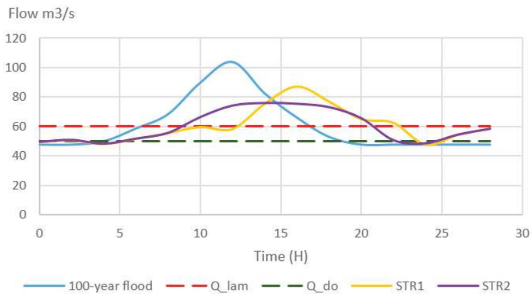

Fig. 7. Outflows downstream during a 100-years flood

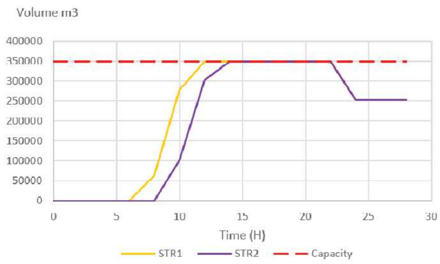

Fig. 8. Reservoir filling evolution during a 100-years flood

Comparing the outflows obtained for the two strategies, it is noticed that the maximum overflow value ($77m^3/s$) reached in the case of $STR2$ is below the one ($87m^3/s$) reached for $STR1$. Thus, $STR2$ successfully store the peak of the flood, while the reservoir in $STR1$ was filled before the arrival of the peak. Furthermore, because the $STR2$ strategy prefer a low amplitude flood than an intense sharp one, the time period where the downstream flow is over Q_{lam} for $STR1$ ($12h$) is shorter than for $STR2$ ($10h$). In figure 8 the maximum capacity of the tank ($350000m^3$) is represented in red discontinuous line and the water volume stored in the tank is given in yellow when the ordinary strategy $STR1$ is applied and in purple for the proposed strategy $STR2$. The storage in the reservoir in the case of $STR1$ starts before the $STR2$ case, and by consequence the tank was filled before the arrival of the peak. Hence $STR2$ allows managers to evacuate citizens and attenuates the potential damages.

5. CONCLUSION

A flood decrease strategy was presented to control a river system equipped with flood diversion areas. The strategy is based on a network flow modeling coupled with a hydraulic simulator to simulate water transfer. Its effectiveness was tested on the Bastillac area for flood events with different characteristics and a 100 years flood case reported. The strategy developed in this paper ensures a weak downstream flow peak and a reduced impact. Future work will focus on finding an optimal frequency for the valves manipulation and on applying a robust algorithm for the estimation, over the time window, of the incoming flow.

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